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ANTENNAS FOR THE VLF REGION AND LF REGION

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FOREWORD

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The studies on the propagation of VLF waves which have been conducted for the past 10 years under the supervision of Doz. Dr. W. Bittorlich, made it necessary right from the beginning to conduct continuous and intensive examinations on the construction of suitable transmitting and receiving antennas. During this period, numerous types of antenna have been calculated, constructed and tested under various conditions. The results of these studies shall now be reported in brief. Derivations and equations shall not be given, quotations of reports and publications shall be made which deal with the respective problems.

ABSTRACT

This is a description of all the transmitting and receiving antennas that have been used for VLF project studies. The antenna efficiency is discussed and helical transmitting antennas are described in a special chapter. Various diagrams plotted in accordance with the described antenna measurements are given.

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS AND SYMBOLS

a [m] antenna radius

$\alpha [m^{-1}] = 2\pi/\lambda$ phase constant

b [kHz] band with of antenna

$\beta [m^{-1}] = \bar{R}_1/2\bar{Z} + \bar{G}_1\bar{Z}/2$ attenuation constant

$\bar{C}_1$ [pF/m] mean capacity per axial unit length of antenna

E_r, E_θ, E_φ electric field strength components

$\varepsilon = \varepsilon_r \varepsilon_o$ dielectric constant

f [Hz] frequency

f_r [Hz] resonant frequency

F [cm²] antenna cross section

$\bar{G}_1$ [mhos] mean value of conduction per axial unit length

h_{eff} [m] effective height of an antenna

H_r, H_θ, H_φ magnetic field strength components

I [amp.] antenna current

I_o [amp.] resonant antenna current

$\bar{L}_1$ [mH/m] mean inductance per axial unit length

K magnetic flux

l [m] half axial length of helical antenna

λ_o km wave length in vacuum

λ km wave length in medium

λ_a wave length along the axis of antenna

$\mu = \mu_r \mu_o$ permeability

n number of turns

ψ pitch angle of antenna

p_1 [m] wire radius without insulation

p_2 [m] wire radius with insulation

Q quality

R [ohms] ohmic resistance

R_o [ohms] input resistance at resonance

$\bar{R}_1$ [ohms] resistance per unit

R_s [ohms] radiation resistance

s	pitch of antenna turns
$S = (\omega\mu/2)^{1/2}$	
σ [mhos/m]	conductivity
$\bar{v}_a$	mean axial phase velocity
W	emitted energy
W^e, W^m	electric, magnetic energy flux
ω	angular frequency
Z	wave resistance
$\bar{Z}$	mean wave resistance

ANTENNAS FOR THE VLF REGION AND LF REGION

I. Introduction

Although great interest was taken in transmitting information through the earth's crust by means of electromagnetic waves, this field of research was fairly new territory. Since the earth's crust represents a dielectric with heavy losses, or a more or less conductive medium, it was necessary to use low frequencies for covering great distances. In this connection, technical difficulties arose when low and very low frequencies of the electromagnetic spectrum were used.

Besides external disturbing influences (electromagnetic disturbing field produced by the sun, in the atmosphere, and by technical equipment), which must be eliminated as far as possible, the construction of "handy" antennas which are small, but effective, is one of the greatest problems. As compared to the wavelength (wavelength at 10 kHz in vacuum for example is 30 km), such antennas must always be very small, i.e., their efficiency will also be very small. These problems are the same for transmitting and for receiving antennas.

Furthermore the problem must be solved whether to use electric or magnetic dipole antennas. For the case of receiving antennas, this problem may be decided upon by brief calculations and technical considerations [1, 2].

Let the transmitting field strength at the point of reception be arbitrarly chosen as $E_{eff} = 50$ millivolts/m. At the receiver side, there is at first an electric dipole with an effective height of $h_{eff} = 2$ m.

The above dipole can be materialized by a vertical wire of 2m length, grounded at one end, having a horizontal antenna branch of 6 m at its upper end. The voltage induced in the dipole then is U_{eff} = $= E_{eff} \cdot h_{eff}$ = 100 millivolts.
The radiation resistance at a frequency of f = 10 kHz (λ_o = 30 km) is the following:

$$R_s = 160 \pi^2 \left(\frac{h_{eff}}{\lambda_o}\right)^2 = 7 \cdot 10^{-6} \text{ ohms.}$$

Let the magnetic dipole be a frame antenna with an area of F = 0.75 m^2 and a number of turns n = 140. The effective height now reads

$$h_{eff} = \frac{2\pi n F}{\lambda_o} = 3 \text{ mm.}$$

The radiation resistance

$$R_s = 80\pi^2 \left(\frac{h_{eff}}{\lambda_o}\right)^2 = 8 \cdot 10^{10} \text{ ohms.}$$

The induced voltage is the following:

$$U_{eff} = 0.15 \text{ millivolts.}$$

This result suggests that the electric dipole is to be preferred, since the voltage induced in it is much higher. Yet, the use of magnetic dipole antennas is more favorable, since the induced antenna voltage may be fully utilized as input voltage for a subsequent amplifier. Tuning to resonance is also easily possible, so that the useful voltage is still increased by Q.

In the case of transmitting antennas, a decision is not so easy, since here the surrounding medium also has some influence. Thus, it has been found out for example [3] that if the wave numbers k^* (ω, σ, ε) are very small, the electric

dipole is preferred as a transmitting antenna under the condition that the production of an adequate antenna current is possible at the same transmitter power as in the case of a similar magnetic dipole.

The transmitting current may be increased by tuning to resonance, the antenna representing the inductance. Tuning to resonance in the case of a magnetic dipole is conducted either by means of capacitances in a parallel or series resonant circuit, or by using self-resonant antennas. In the LF region and even more so in the VLF region, such self-resonant antennas of small dimensions are very difficult to construct. This problem is dealt with in Chapter III, helical antennas.

II. Transmitting antennas

In the VLF region, electromagnetic fields produced by antennas that can be built in practice, may be described by equations for the Hertz dipole, since the condition that the antenna must be small as compared to the wavelength, is satisfied only too well. For the electric or magnetic dipole the following relations are valid (for reasons of simplicity, only the dependence of quantities is given that may be chosen arbitrarily):

$$E_r,\ E_\vartheta,\ H_\varphi \sim I \cdot dl \quad \text{and} \quad H_r,\ H_\vartheta,\ E_\varphi \sim n \cdot I \cdot F, \text{ respectively.}$$

I... antenna circuit, dl... length of antenna

n... number of turns, F ... antenna cross section.

If the antenna length and cross section are limited (e.g., by the gallery), the field strength components may be increased only by increasing the antenna current. This, however, is also limited: in an electric dipole owing to the capacitance between the ends of the dipole and owing to antenna voltage, whereas in a magnetic dipole owing to losses in the winding. The increasing antenna inductance also puts a limit. [4]

What antenna type is to be preferred for the frequency region in question shall be examined in the present chapter by comparing the radiated energies [5]. For this purpose it must be taken into account that an antenna in air electrically may be looked upon as a combination of its ohmic resistance and radiation resistance. In air or in vacuo, the radiation resistance is determined by integrating the Pointing vector in the far field over a spherical surface of any size around the antenna. Division of this integral by the square maximum current yields the radiation resistance. In an antenna embedded in a conducting medium, the resistance produced by the surrounding medium must still be added. Experience shows that this resistance is larger for an electric dipole than it is for a magnetic one, except for the case of $k^{e}(\omega, \sigma, \varepsilon)$ being small (cf. introduction).

Calculating the energy flux through a spherical surface having the radius r, we obtain [5]:

1. For the electric dipole

$$W^{e} = \frac{8\pi}{3} \left(\frac{I\ l}{4\ \pi}\right)^{2} \frac{e^{-2\ k\ r}}{r} \left[\omega\mu k + \frac{2\ S\ k}{r} + \frac{2\ S}{r^{2}} + \frac{1}{r^{3}}\right]$$

or if $r \gg \lambda$

$$W^{e}_{r \gg \lambda} = W^{e}_{v} \ \frac{e^{-4\pi\ r/\lambda}}{\sigma\lambda} \ ,$$

with $W_v^e = 40\pi^2(\frac{I\,l}{\lambda})^2$ being the value for vacuum.

2. For the magnetic dipole:

$$W^m = (\frac{K\,l}{\lambda})^2 \frac{e^{-4\pi\, r/\lambda}}{\sigma\lambda}\left[1 + \frac{\lambda}{4\pi r}\right]$$

or if $r \gg \lambda$

$$W^m_{r \gg \lambda} = W_v^m \frac{\sigma\lambda}{2\pi} e^{-4\pi\, r/\lambda}$$

with $W_v^m = \pi/3Z\,(\frac{K\,l}{\lambda})^2$ being the value for vacuum,

$S = (\omega\mu/2)^{1/2}$, Z ... wave resistance $\approx \sqrt{\frac{\mu}{\varepsilon}}$ (for other symbols see list of symbols and abbreviations).

Let us now assume that there is a radius r so that the energy flux of the two dipole types through a spherical surface of the same radius is equal. We may thus compare the electric and magnetic energy flux

$$\frac{W_v^e}{W_v^m} = \frac{18 \cdot 10^9}{f}\,\sigma\,\frac{h_2(r)}{h_1(r)} \quad \text{in vacuo.}$$

For another radius r', this comparison may be made also for a medium, thus yielding

$$\frac{W^e}{W^m} = \frac{W_v^e}{W_v^m}\,\frac{18 \cdot 10^9}{f}\,\sigma\,\frac{h_1(r')}{h_2(r')} \quad .$$

Substituting W_v^e/W_v^m as above, we obtain

$$\frac{W^e}{W^m} = \frac{h_1(r')\,h_2(r)}{h_2(r')\,h_1(r)} \quad .$$

Assuming that $r' \gg \lambda$, we obtain the following expression:

$$\frac{W^e}{W^m} \cdot \frac{h_2(r)}{h_1(r)} < 1 .$$

This, however, means that $W^m > W^e$.

To this result it must be added that this inequation is valid only if σ and f assume certain values. As has been shown in [5], the inequality is valid for the used frequencies and conductivities. As a result it may be said that even if the energy radiation of the electric dipole in air exceeds that of the magnetic dipole by several powers of ten (cf. the subsequent calculation), in a conductive medium it will only be a fraction of its value.

This statement, however, holds only with some other restrictions: ε small, $r \gg \lambda$. A decision of what type of antenna is to be used is still open. The question arises, whether antennas in a dissipative medium may be compared generally, or whether exact data is necessary for the conditions of their use. Do optimum antennas exist at all? Let me describe them as a structure permitting the transmission of information over a requested distance in a dissipative medium at minimum transmitter power.

If we want to compare various antennas, certain restrictions must be made as to the conditions under which they are to be used [3]:

(1) Requirements for flexibility of frequency, sufficient band width and local mobility shall be completely neglected.

(2) The properties of the surrounding medium must always be constant.

(3) The frequency must be constant.

(4) The cavities in the lossy medium that surrounds the antennas must always have the same size and shape.

(5) The antennas themselves must have about the same size.
(6) The antennas must operate under constant power conditions.
(7) The input resistance of the antennas to be compared must be known.

This shows that a number of conditions must be satisfied in order to permit a useful comparison between various antennas.

An example is going to demonstrate how low the emitted power actually is as compared to the power required when using antennas that are small compared to the wavelength.

The portable transmitting unit with antenna SA XI described in [6] (cf. Chapter VI., list of antennas) had the following data of operation:

$f = 120$ kHz (which corresponds to a vacuum wavelength of $\lambda_o = 2.5$ km),
$I_o = 1.4$ a, antenna resonance current reached by tuning to resonance by capacitors,
$R = 0.5$ ohms antenna resistance
$n = 16$, number of turns
$F = 1.5$ m^2, area of cross section.

The power put into the antenna was 5.4 watts. The wavelength for a medium with an assumed dielectric constant of $\epsilon = 10$ is $\lambda = 0.8$ km, since $\lambda = \frac{\lambda_o}{\sqrt{\epsilon\mu}}$ $\mu = 1$.
The emitted energy is obtained from

$$W = \frac{R_s I_o^2}{2} .$$

The radiation resistance $R_s = 8\pi^2 (\frac{h_{eff}}{\lambda})^2$ according to the above data yields

$$R_s = 4.4 \cdot 10^{-5} \text{ ohms},$$

with the effective height being $h_{eff} = \frac{2\pi n F}{\lambda}$ calculated from $h_{eff} = 0.19$ m.

The radiation resistance is smaller than the total ohmic losses by powers of ten. As it is an essential quantity in the equation of emitted power, the latter is also very low:

$$W^m = \frac{R_s I_o^2}{2} = 4{,}3 \cdot 10^{-5} \text{ watts.}$$

For better comparison, the power emitted by a simple vertical dipole 10 m high is being calculated. The operational data is the same as above.

$$W^e = \frac{I_o^2 R_s}{2} .$$

The formulas for calculating R_s and h_{eff} have been taken from [7].

$$R_s = 1579\left(\frac{h_{eff}}{\lambda}\right)^2 , \quad h_{eff} = \frac{1}{\alpha} \frac{1 - \cos(\alpha h)}{\sin(\alpha h)} ,$$

with $\alpha = 2\pi/\lambda$ and h = 10m (height of the electric dipole). With the above values we obtain

$h_{eff} = 5$ m

$R_s = 6{,}2 \cdot 10^{-2}$ ohms, and

$W^e = 6 \cdot 10^{-2}$ watts.

Both calculations have been made for the conditions of an air-filled space, for which the electric antenna is clearly advantageous. For antennas embedded in a medium, $W^m > W^e$ is valid as shown above, i.e., the magnetic dipole is more favorable. The shorter wavelength for a medium ($\epsilon = 10$) has been used instead of the vacuum wavelength so that the ratio antenna length/wavelength need no longer be taken into account when comparing the energy emission in vacuo (or air) and in a medium. Only a fraction of the total antenna power is available for its actual radiation, the rest is consumed by ohmic resistances.

The antenna efficiency is thus very low with the given arrangement.

Furthermore, the above definition of the radiation resistance and of the efficiency fails if the antenna is located in a medium. In a lossy medium, the integral depends on the spherical radius, i.e., a radius arbitrarily large can no longer be permitted. The only factors that may be compared in the radiation field of antennas are the components of the electric or magnetic field strength and their combinations in phase.

These few considerations have already shown that the problem of an optimum antenna for a certain medium cannot be solved in this general form. A solution of this problem would be easier if the influence of all factors on the input resistance of the antenna were known precisely. As it may also depend on the shape and size of the cavity, an input resistance as suitable as possible (i.e., a low one in most cases) is not only a technical problem.

III. Helical antennas

It has been mentioned at the beginning that the use of self-resonant antennas is a way of increasing the antenna current. Their input impedance, however, is not easily adapted to a feeder line or a transmitter output, since the self-resonant frequency of such antennas (if they are small) is much higher than the operational frequency.

Preliminary examinations of small helical antennas showed that this shape produces self-resonant phenomena in the desired frequency regior `. Lukavec in his report [3] tried

to find a relation between the antenna dimensions (length, diameter, pitch, wire thickness, insulating material) and the self-impedance or resonant frequency and the field structure in the surrounding medium. Various antennas were built and their properties were studied above ground and in the mine, in air and in water. This chapter is going to review in brief the possibilities of calculating theoretically small helical antennas. For the purpose of calculating the phase velocity and the wave resistance of a helix, a network model is used (according to HEYNISCH [8]) of unit quadrupoles, stating the mean inductance and capacitance per unit length (Fig. 1).

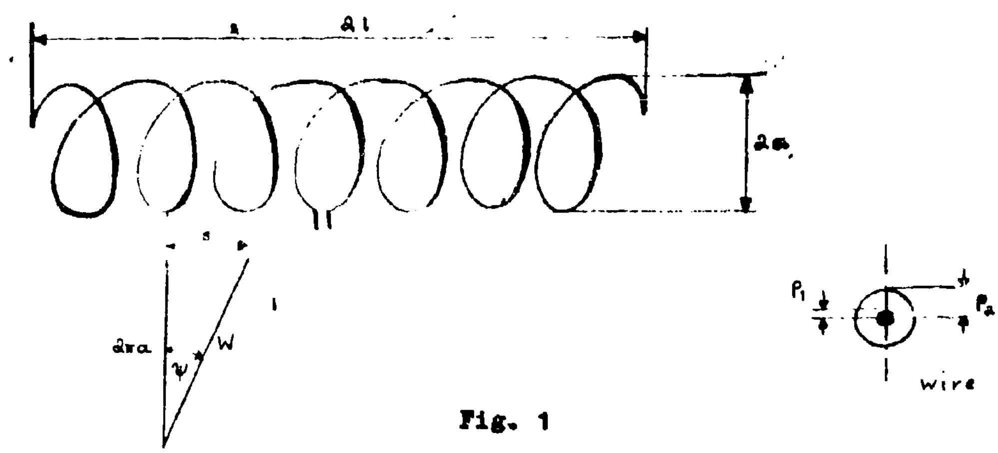


Fig. 1

Fig. 1 illustrates the antenna geometry as follows:

2 l ... total axial antenna length [m]

2 a ... antenna diameter (center to center of wire) [m]

s ..... pitch (center to center of wire) [m]

ψ ..... pitch angle [degrees]

n ..... total number of turns

p_1 .... wire radius without insulation

p_2 .... wire radius with insulation.

On the whole, the antenna is an air coil with open ends, separated and symmetrically fed in the middle. This method of feeding need not be the best one, but owing to the symmetry and absence of grounding problems it is the simplest method, theoretically and experimentally.

An alternating current flowing through the antenna leads to a periodic setting-up and breaking-down of opposite voltages to the left and to the right of the antenna center in accordance with a mutual capacitance of the two antenna halves, with an inductive resistance by the magnetic field it produces. We thus obtain a mean inductance ($\bar{L}_1$) and a mean capacitance ($\bar{C}_1$) per axial unit length. The mean axial phase velocity of the current thus reads

$$\bar{v}_a = (\bar{L}_1 \cdot \bar{C}_1)^{-1/2} .$$

As the two ends of the antenna are open, they reflect the current ideally (current nodes) thus causing the formation of standing waves. The lowest axial resonance is characterised by a current bulge in the middle and zero current at the ends. In this case, the axial wavelength is

$$\lambda_a = 4\ l.$$

The lowest corresponding resonant frequency is

$$f_r = \frac{v_a}{\lambda_a} = \frac{v_a}{4\ l} .$$

In [3] a formula is derived in detail for calculating the input resistance:

$$R_o = \bar{Z}^2 \left[\frac{\bar{G}_1 \cdot l}{2} + \frac{x^2}{8 \cdot \bar{R}_{1p} \cdot l} \right] + \frac{\bar{R}_{1s} \cdot l}{2} \qquad [\text{ohms}] .$$

The wave resistance $\bar{Z}$ thus holds a key position so that it will be kept as small as possible in order to make the input resistance as low as possible.

Furthermore, formulas were found for calculating the resonant frequency and the wave resistance. Since

$$f_{res} = v_s/\lambda_s = 1/4 \cdot l\sqrt{\bar{L}_1\bar{C}_1} \quad \text{and } \bar{Z} = \sqrt{\bar{L}_1/\bar{C}_1}$$

it was necessary to calculate at first $\bar{L}_1$ and $\bar{C}_1$. While the calculation of $\bar{L}_1$ involved no difficulties - at low frequencies, the inductance of a long air coil may be used - the calculation of $\bar{C}_1$ yielded a discrepancy between theory and experiment (about 30%). This was, because the "input region" of the antenna had not been taken into account which in the case of a helical antenna is formed by the two central turns, contributing to the capacitance much more than had been expected. Thus, another term had to be added to the formula for $\bar{C}_1$ which takes into account the capacitance of the input region.

In order to on the one hand reduce the resonant frequency of the antenna at constant dimensions and on the other hand check the theory of input impedance, the antennas were also located in a cavity filled with water. The antenna inductance thus is not changed, whereas the capacitance is increased considerably. The resonant frequency decreased by one to two powers of ten, the mean wave resistance also decreased.

For the current and voltage distribution, the following conditions were found:

$$I(x) \approx I(o) \cos(\alpha x) \quad U(l) = \frac{-i\ U(o)}{\sinh \beta\ l} \approx \frac{-i\ U(o)}{\beta\ l}$$

$$\text{if } \beta\ l \ll 1$$

$\alpha = 2\pi/\lambda$ ... phase constant, β ... attenuation constant.

The current distribution governs the effective magnetic moment of the antenna and thus also the magnetic induction produced by the antenna at a certain point of measurement.

For calculating the far field we also use a model. WHEELER [9] thus describes the far field of self-resonant helical antennas as a combination of magnetic and electric dipoles in vacuo.

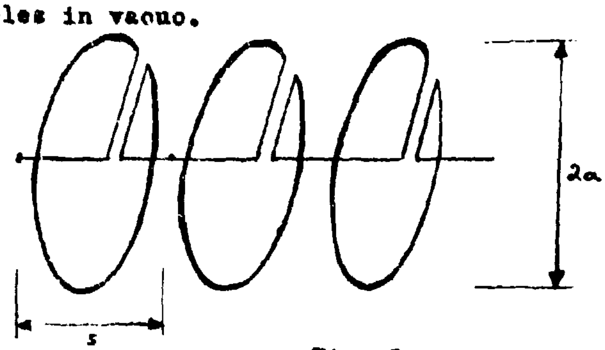


Fig. 2

Fig. 2 shows a method of separating every turn of the helical antenna into two "radiating" components: one axial distance equal to the pitch s, and a circular loop having the area A, normal to the helical axis. The electric dipole therefore is assumed to be the distance n·s = 2·l, the magnetic dipole is assumed to be the sum of all areas = n.A. The length of the electric dipole may be very small, if the winding is tight. The above assumption is based on the condition that the antenna dimensions are small as compared to the wavelength, which in the present case has been verified. Both dipole components have the same direction of axis. We obtain three components of electric field strength and three components of magnetic induction. Measurements were made only of the magnetic components, which proved to be favorable (cf. Chapter IV, receiving antennas). The equations for the field strength components have been collected in [3]. The wave number k contained therein is replaced by the complex wave number k^* for

transition to a dissipative medium:

$$k^* = k_1 - ik_2$$

k_1 ... phase constant, k_2 ... attenuation constant.

For checking the theoretical results, numerous helical antennas have been built with different numbers of turns and different lengths. The radiation fields they produce were studied in detail. The antennas were set up above ground, as well as in mine galleries filled with air and with water, respectively. The helical antennas have not been used as receiving antennas, because they are clumsy, highly sensitive when being approached, and owing to their self-resonance, their frequency can be varied little.

The first helical antenna for this project was built by W. BITTERLICH in 1964 and was operated at 110 kHz in a basin filled with water. This antenna as well as a number of other antennas were based on the following circuit diagram [10]:

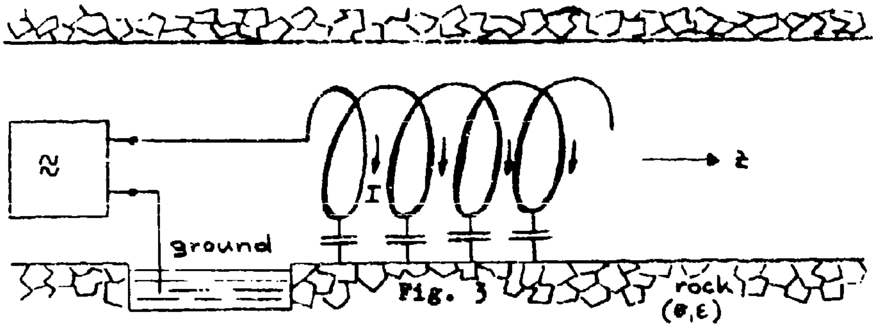


Fig. 3

The problems that arise with this method of feeding (at the end) and grounding, so far have not been solved satisfactorily. Consequently, symmetrically fed antennas with open ends were used for further examinations. Great care was taken when measuring the impedance of the helix, since this quantity must be known for optimum adaptation to the generator.

The following end-fed antennas were built and tested: WA 1, WA 2, WA 3, WA 4 (for detailed data see Cahpter VI). The lowest resonant frequency of 24 kHz was found in WA 3. Attempts were made to further reduce this resonant frequency value by putting small inductances into the antenna winding. The result was good, but the simultaneous decrease in impedance toward the point of resonance was not distinct enough. For the largest distance that could be covered (700 m) the data was the following:

Antenna: WA 3; frequency: 24 kHz; medium: $\mathcal{E} = 10$; transmitter power: 95 watts; angle between helix and ferrite antenna: $\vartheta = 40^0$; receiving antenna: ferrite antenna, 50 cm long; field strength: $(4{,}36 \pm 0{,}2)\cdot 10^{-12}\ \frac{\text{volts . sec}}{\text{m}^2}$.

Symmetrically fed antennas were tested on the following model [3]: H 848, H 200, H 600, H 772, H 1362 (for detailed data see Chapter VI). The example of H 772 which yielded very good results is used to show the relation between theory and experiment.

H 772

$l = 1{,}01$ m

$\varepsilon_{ri} = 1{,}4$

$a = 1/2\pi$ m

	theor.	exp.	ΔW (%)
$\bar{L}_1$ [mH/m]	14,7	14,2	+ 3,5
$\bar{C}_1$ [pF/m]	32,2+18,0 = 50,2	51,0	- 1,5
$\bar{Z}$ [k ohms]	17,1	16,7	+ 2,6
f_r [kHz]	291	294,2	- 1,1
R_0 [ohms]		85	
β [m^{-1}]		$5{,}09 \cdot 10^{-3}$	
Q quality		318	
b [kHz] band width		0,925	

Table I and Fig. 4 show the input impedance of H 772 as dependent on frequency.

The result of measurements with H 772 W (W for water) is to show the change of properties of an antenna submerged in water. (Table II and Fig. 5).

H 772 W

	water	air
f_r [kHz]	5,48	294,2
$\bar{C}_1$	141 nF/m	51,0 pF/m
$\bar{Z}$	322 ohms	16,7 k ohms
R_o [ohms]	122	85,0
s [m^{-1}]	0,379	$5{,}09 \cdot 10^{-3}$
Q	3,66	318
b [kHz]	1,5	0,925

Note the extremely low resonant frequency (5,48 kHz).

Summing up the results we may say that theory may be used for explaining the phenomena observed in the region of lowest resonant frequency. Wave resistance and resonant frequency may be calculated in advance when using a carefully constructed antenna. The input resistance at resonance and all the quantities resulting from it cannot be calculated precisely. Yet we may say that the following types are preferred: antennas whose length is large as compared to their diameter and antennas that have a great pitch. These requirements, however, contradict the desire for low resonant frequency. Hence, a compromise must again be made.

The distances reached with the above antenna arrangement are of interest for communication through the earth's crust:

A distance of 600 m through dolomite rock was reached with H 772 at an antenna current of 600 milliam. (transmitter

II 772

TABELLE I

IMPEDANZ EINER WENDEL

F [KHZ]	R [K OHM]	C [NF]	RE Z [K OHM]	IM Z [K OHM]	BETR Z [K OHM]	D RE Z	D IM Z	D BETR Z
100,00	500,000	0,051	,194/+01	-,310/+02	,311/+02	0,070	0,110	0,110
150,00	300,000	0,053	,133/+01	-,199/+02	,199/+02	0,070	0,110	0,109
200,00	250,000	0,062	,657/+00	-,128/+02	,128/+02	0,070	0,110	0,110
260,00	200,000	0,098	,194/+00	-,624/+01	,624/+01	0,070	0,110	0,110
270,00	111,000	0,162	,119/+00	-,363/+01	,363/+01	0,070	0,110	0,110
275,00	50,000	0,213	,147/+00	-,270/+01	,271/+01	0,070	0,110	0,110
280,00	30,000	0,282	,134/+00	-,200/+01	,201/+01	0,070	0,110	0,109
285,00	20,000	0,387	,103/+00	-,143/+01	,143/+01	0,070	0,110	0,109
287,00	15,000	0,407	,122/+00	-,135/+01	,135/+01	0,069	0,109	0,109
289,00	11,000	0,456	,131/+00	-,119/+01	,120/+01	0,069	0,109	0,109
290,00	10,000	0,560	,951/-01	-,970/+00	,975/+00	0,069	0,109	0,109
292,00	2,010	1,320	,813/-01	-,396/+00	,404/+00	0,067	0,107	0,105
294,00	0,250	3,000	,856/-01	-,118/+00	,146/+00	0,043	0,083	0,069
294,20	0,085	0'	,849/-01	0	,849/-01	0,010	0,050	0,010
302,00	39,800	-0,274	,927/-01	,191/+01	,192/+01	0,070	0,110	0,110
305,00	169,000	-0,129	,967/-01	,404/+01	,404/+01	0,070	0,110	0,110
320,00	401,000	-0,018	,189/+01	,275/+02	,275/+02	0,070	0,110	0,109
332,00	93,000	-0,013	,126/+02	,318/+02	,342/+02	0,059	0,099	0,094
354,00	360,000	0,009	,680/+01	-,490/+02	,494/+02	0,068	0,108	0,108
380,00	50,100	0,[illegible]9	,986/+00	-,695/+01	,702/+01	0,068	0,108	0,108
400,00	22,200	0,096	,747/+00	-,400/+01	,407/+01	0,067	0,107	0,106

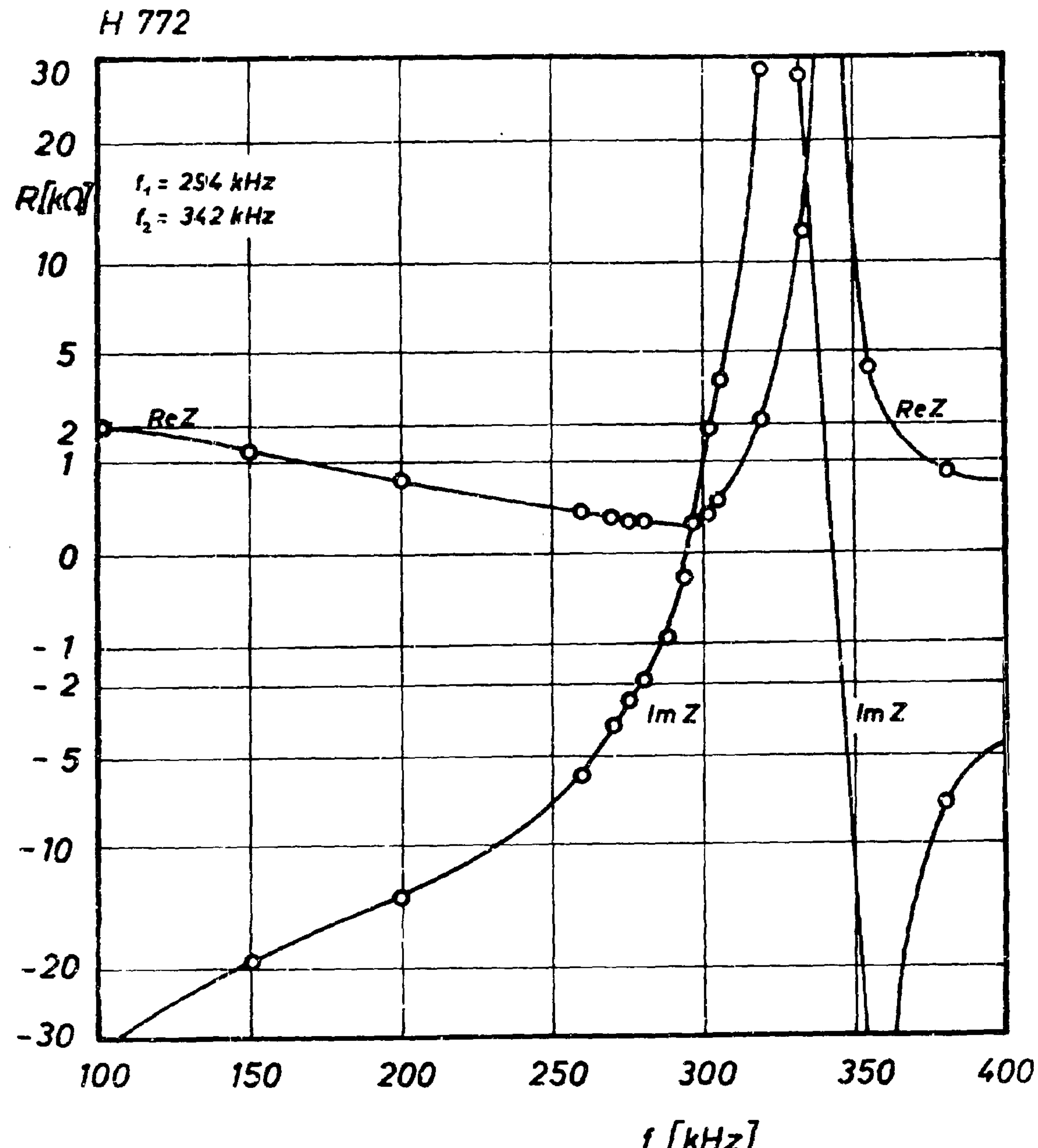

H 772
f_1 = 294 kHz
f_2 = 342 kHz
R[kΩ]
30
20
10
5
2
1
0
- 1
- 2
- 5
-10
-20
-30
Re Z
Im Z
100
150
200
250
300
350
400
f [kHz]

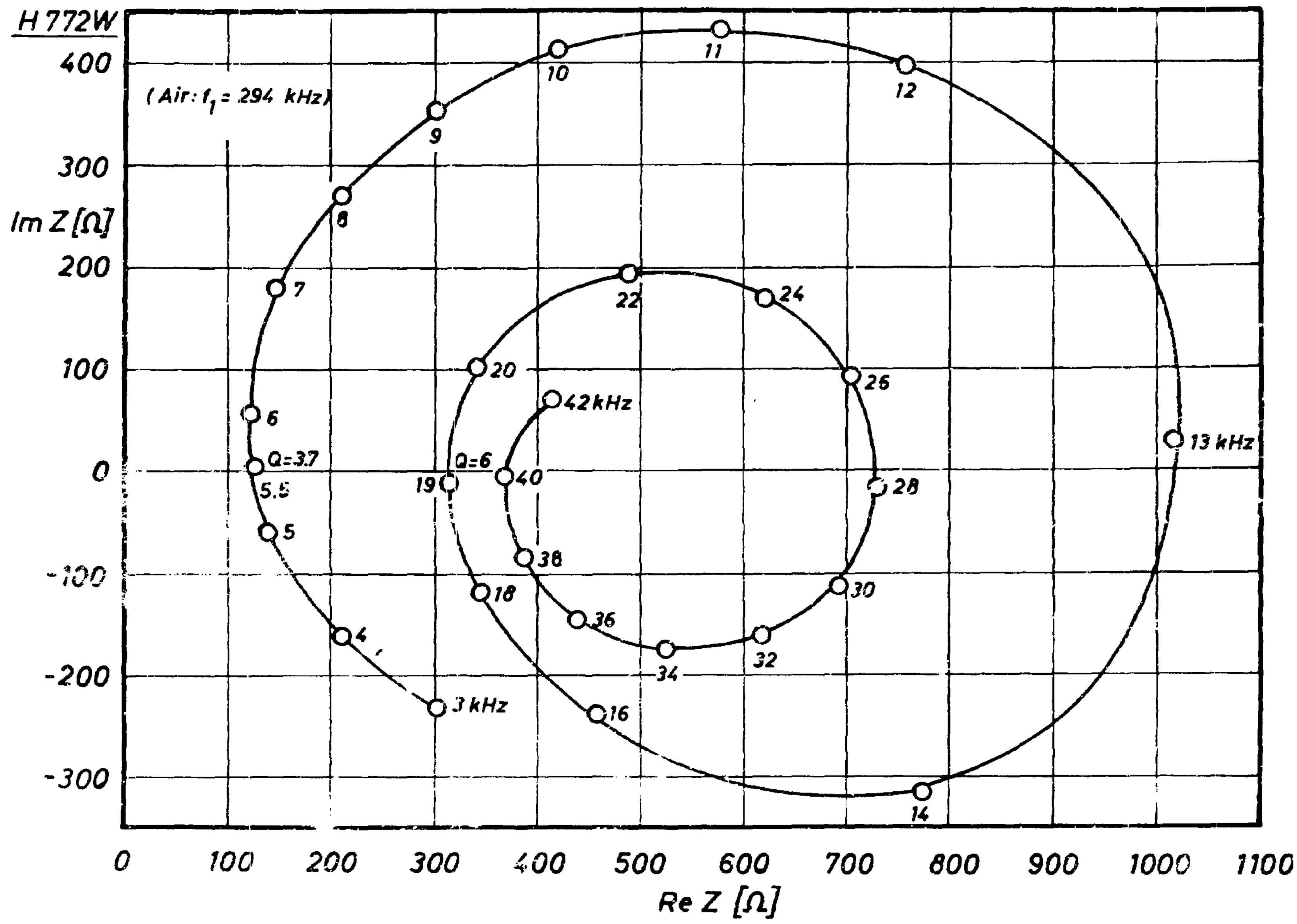
Fig 4

B 772 W

TABELLE II

IMPEDANZ EINER WENDEL

F [KHZ]	R [K OHM]	C [NF]	RE Z [K OHM]	IM Z [K OHM]	BETR Z [K OHM]	D RE Z	D IM Z	D BETR Z
3,00	0,485	84,300	,304/+00	-,234/+00	,384/+00	0,025	0,065	0,040
4,00	0,336	92,300	,209/+00	-,162/+00	,265/+00	0,025	0,065	0,040
5,00	0,167	80,700	,141/+00	-,599/-01	,153/+00	0,016	0,056	0,022
5,20	0,142	57,700	,132/+00	-,354/-01	,137/+00	0,013	0,053	0,015
5,40	0,127	20,000	,126/+00	-,108/-01	,126/+00	0,010	0,050	0,011
5,48	0,123	-0,880	,122/+00	,458/-03	,122/+00	0,010	0,050	0,010
5,60	0,122	-28,000	,120/+00	,144/-01	,121/+00	0,011	0,051	0,011
5,80	0,130	-71,000	,116/+00	,392/-01	,123/+00	0,014	0,054	0,018
6,00	0,151	-95,000	,116/+00	,631/-01	,132/+00	0,019	0,059	0,028
7,00	0,364	-74,200	,150/+00	,179/+00	,234/+00	0,037	0,077	0,060
8,00	0,536	-45,100	,216/+00	,262/+00	,340/+00	0,038	0,078	0,062
9,00	0,678	-29,600	,296/+00	,336/+00	,448/+00	0,035	0,075	0,058
10,00	0,830	-19,200	,414/+00	,414/+00	,586/+00	0,030	0,070	0,050
12,00	0,963	-7,200	,756/+00	,395/+00	,853/+00	0,019	0,059	0,027
14,00	0,899	5,100	,773/+00	-,311/+00	,833/+00	0,016	0,056	0,021
16,00	0,588	9,000	,458/+00	-,243/+00	,519/+00	0,019	0,059	0,028
18,00	0,388	8,200	,343/+00	-,123/+00	,365/+00	0,015	0,055	0,019
19,90	0,312	1,050	,311/+00	-,127/-01	,311/+00	0,010	0,050	0,010
20,00	0,345	-1,850	,342/+00	,274/-01	,343/+00	0,010	0,050	0,011
22,00	0,569	-5,090	,490/+00	,196/+00	,528/+00	0,016	0,056	0,021
24,00	0,670	-2,800	,620/+00	,175/+00	,644/+00	0,013	0,053	0,016
26,00	0,716	-1,130	,703/+00	,930/-01	,709/+00	0,011	0,051	0,011
28,00	0,726	0,108	,725/+00	-,100/-01	,725/+00	0,010	0,050	0,010
30,00	0,711	1,100	,695/+00	-,102/+00	,703/+00	0,011	0,051	0,012
32,00	0,666	2,050	,619/+00	-,170/+00	,642/+00	0,013	0,053	0,016
34,00	0,582	2,790	,519/+00	-,180/+00	,549/+00	0,014	0,054	0,019
36,00	0,479	3,120	,429/+00	-,145/+00	,453/+00	0,014	0,054	0,018
38,00	0,406	2,650	,380/+00	-,978/-01	,393/+00	0,012	0,052	0,015
40,00	0,371	0,146	,370/+00	-,504/-02	,370/+00	0,010	0,050	0,010
42,00	0,428	-1,590	,414/+00	,744/-01	,421/+00	0,011	0,051	0,012


H 772W
(Air: f_1 = 294 kHz)
Im Z [Ω]
Re Z [Ω]
400
300
200
100
0
-100
-200
-300
0
100
200
300
400
500
600
700
800
900
1000
1100
3 kHz
4
5
5.5
Q=3.7
6
7
8
9
10
11
12
13 kHz
14
16
18
19
Q=6
20
22
24
26
28
30
32
34
36
38
40
42 kHz

power 21 watts) and a frequency of 294 kHz.

A distance of 1,6 km (which is the greatest length possible in our terrain) was reached with H 772 W (i.e., submerged in water) at a frequency of 5,5 kHz and an antenna current of about 400 milliamp. (transmitter power 21 watts). This comparison shows that the same antenna shows better results when the resonant frequency is reduced.

IV. Receiving antennas

In Chapter I it has already been said that magnetic dipoles are well suited receiving antennas. The most favorable types shall now be described [1].

The voltage induced in a frame antenna is

$$U_{ind} = 2\pi f \cdot n \cdot F \cdot B$$

with f being the frequency, B = magnetic induction, n = number of turns, F = antenna area. The quantities that may be arbitrarily chosen when constructing an antenna are the number of turns and the antenna area which, however, should both be as large as possible. An increase of the number of turns causes an increase of the losses R_v of the resonant circuit, if the antenna represents the inductance of a parallel resonant circuit (Fig. 6).

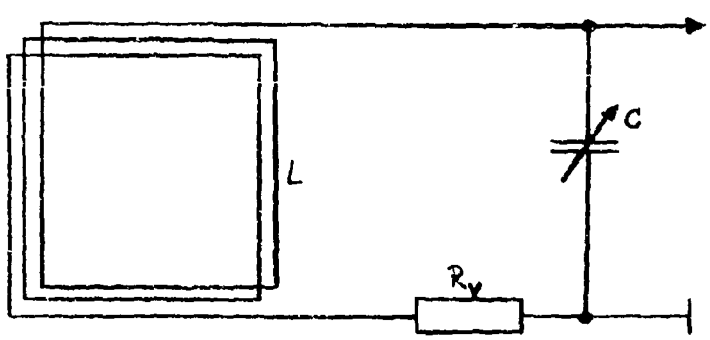


Fig. 6

A large-area frame antenna is, however, highly sensitive to touch, a fact which is very disadvantageous during so-called directional measurements. The area must therefore be reduced to a minimum whereas the reduction of induced voltage caused by it must be compensated by using ferromagnetic material of high permeability. The above equation then reads as follows:

$$U_{ind} = 2\pi f \cdot n \cdot F \cdot B \cdot \mu_{eff} \; (Q),$$

μ_{eff} = effective or shear permeability of the ferrite, Q = quality of oscillating circuit.

If the radiation resistance of such an antenna is to be calculated, we need the effective height which is

$$h_{eff} = \frac{2\pi n \cdot F}{\lambda} \; \mu_{eff}.$$

We thus obtain

$$R_s = 320\pi^4 \left(\frac{n \cdot F \cdot \mu_{eff}}{\lambda^2}\right)^2$$

for the radiation resistance (cf. also page 2).

What has been said above also gives some clues as to the dimensioning of ferrite antennas. In resonance tuning, n must be chosen so that a given frequency region may be covered with the variable capacitance. n cannot be chosen arbitrarily, not even when connecting the antenna aperiodically with the subsequent amplifier, because self-resonance phenomena would occur at a certain value of inductance. F is given by the cross section of the ferrite materia, while μ_{tor} should be chosen in accordance with the frequency region. μ_{eff} is calculated from

$$\mu_{eff} = \frac{\mu_{tor}}{1 + \frac{N}{4\pi}(\mu_{tor} - 1)} .$$

μ_{tor} is the initial or toroid permeability, N is a quantity depending on the ratio rod length/diameter. As to the dimensioning of ferrite antennas see [1], [2], or [5].

The following example is given for better understanding: an antenna which has been used in practice:

Unsymmetric VLF ferrite antenna for the region 1 ... 20 kHz. Rod made of 6 tube cores, diameter d = 19 mm, diameter of bore = 9 mm, material: Siferrit 1100 N 22 with μ_{tor} = 1300, length l = 980 mm, μ_{eff} = 480, n = 2400 (8 short cross winding coils).

Electric data: L = 2,19 H, R (D.C.) = 52 ohms, Δf = = 10 Hz at 3 kHz and Δf = 75 Hz at 10 kHz. U_{eff} was $\sim$ 300 millivolts at E_{eff} = 50 millivolts/m, i.e., three times as high as the theoretical value of an electric dipole (cf. introduction).

There exist two possibilities of eliminating the sensitivity to touch. The first one would be an electrostatic shield by means of a slotted copper cylinder. The second one: rendering the antenna symmetrical (Fig. 7).

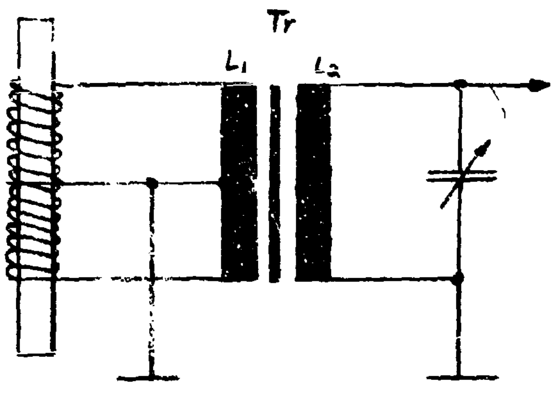


Fig. 7

As to the dimensioning of the transducer see [11].

V. Field strength profiles and directional patterns

Two methods of measurement and evaluation are used for studying the propagation mechanism of (V)LF waves:

1. Profile measurements

In this method, the field strength is measured as dependent on the distance r from the transmitter. Position of antenna and antenna current are kept constant, i.e., the effective moment of the transmitting dipole remains constant.

Fig. 8-11 show such profile measurements for the VL frequencies of 3 and 10 kHz [6], Fig. 12 and 13 show them for the L frequency of 120 kHz [12]. The conductivity σ [mhos/m] is used as a parameter.

2. Directional patterns

A directional pattern is obtained by the well-known method of measuring the field strength values around the transmitting antenna at constant distance. Since this is practically impossible in a mine, the transmitting antenna was rotated and the receiving antenna was left at one point. A specially designed bearing head free of metal [5] made it possible to find the field strength components and detect their direction in space.

Fig. 14-17 show directional patterns for the most frequently used frequencies of 3 and 10 kHz, Fig. 18-21 for 120 kHz. σ is again given as a parameter.

VI. List of the antennas that have been used

This chronological list reviews all antennas that have been built for the VLF project and their technical data as far as available.

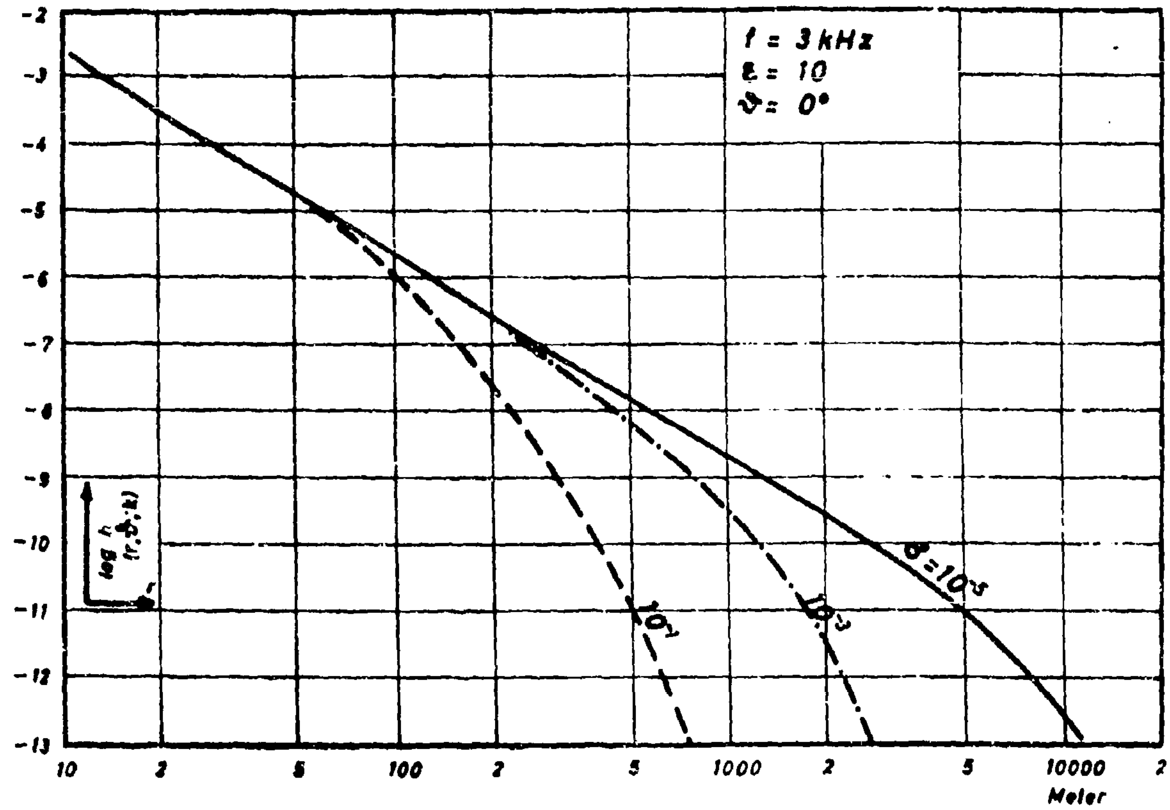
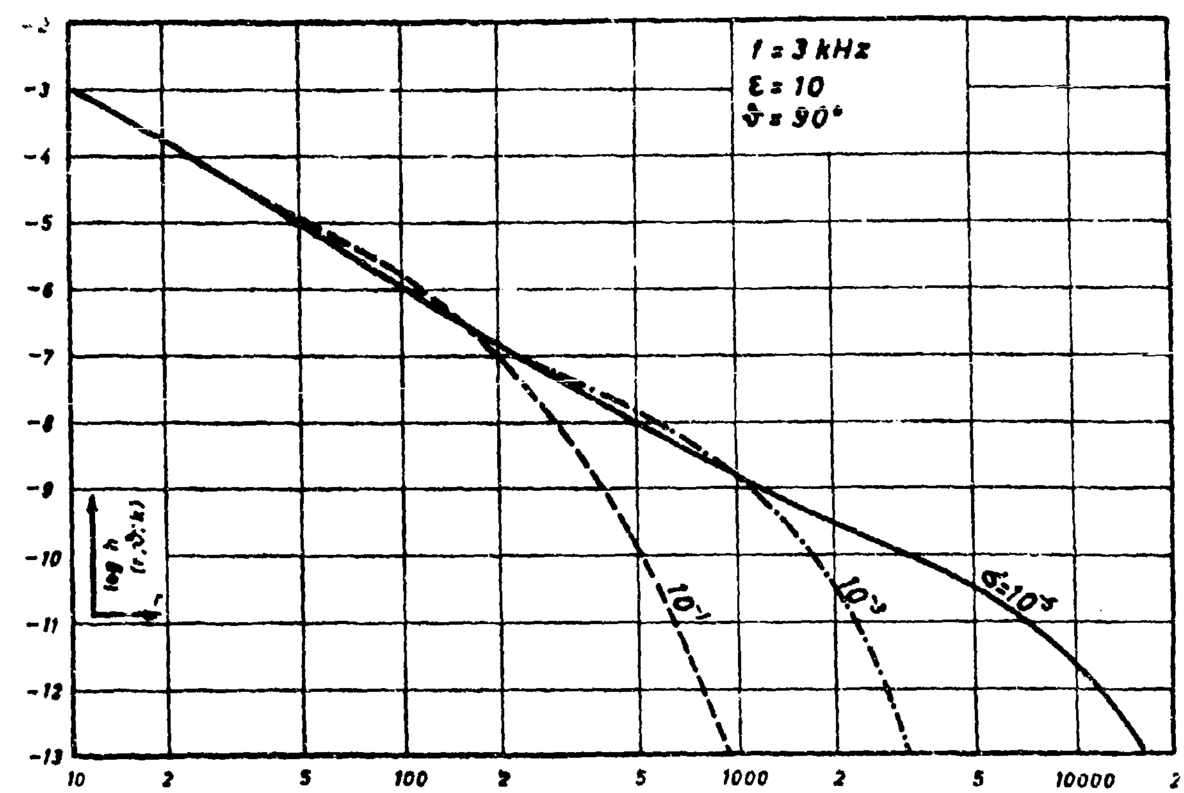

f = 3 kHz
ε = 10
ϑ = 0°
log h (r, ϑ; k)
r
σ=10⁻⁵
10⁻³
10⁻¹
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
10
2
5
100
2
5
1000
2
5
10000
2
Meter

Abb. 8


f = 3 kHz
ε = 10
ϑ = 90°
log h (r, ϑ; k)
r
σ=10⁻⁵
10⁻³
10⁻¹
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
10
2
5
100
2
5
1000
2
5
10000
2

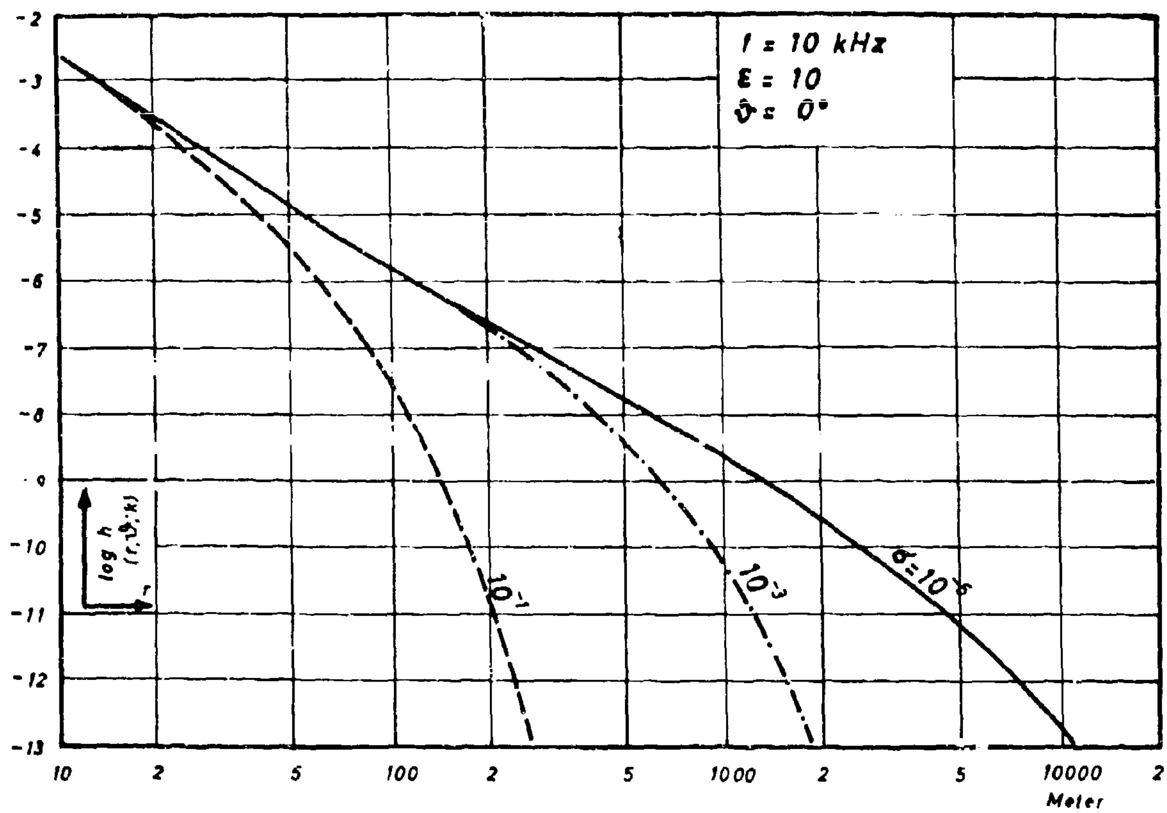

f = 10 kHz
ε = 10
ϑ = 0°
log h (r, ϑ; k)
r
10⁻¹
10⁻³
σ=10⁻⁵
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
10
2
5
100
2
5
1000
2
5
10000
2
Meter

Abb.10

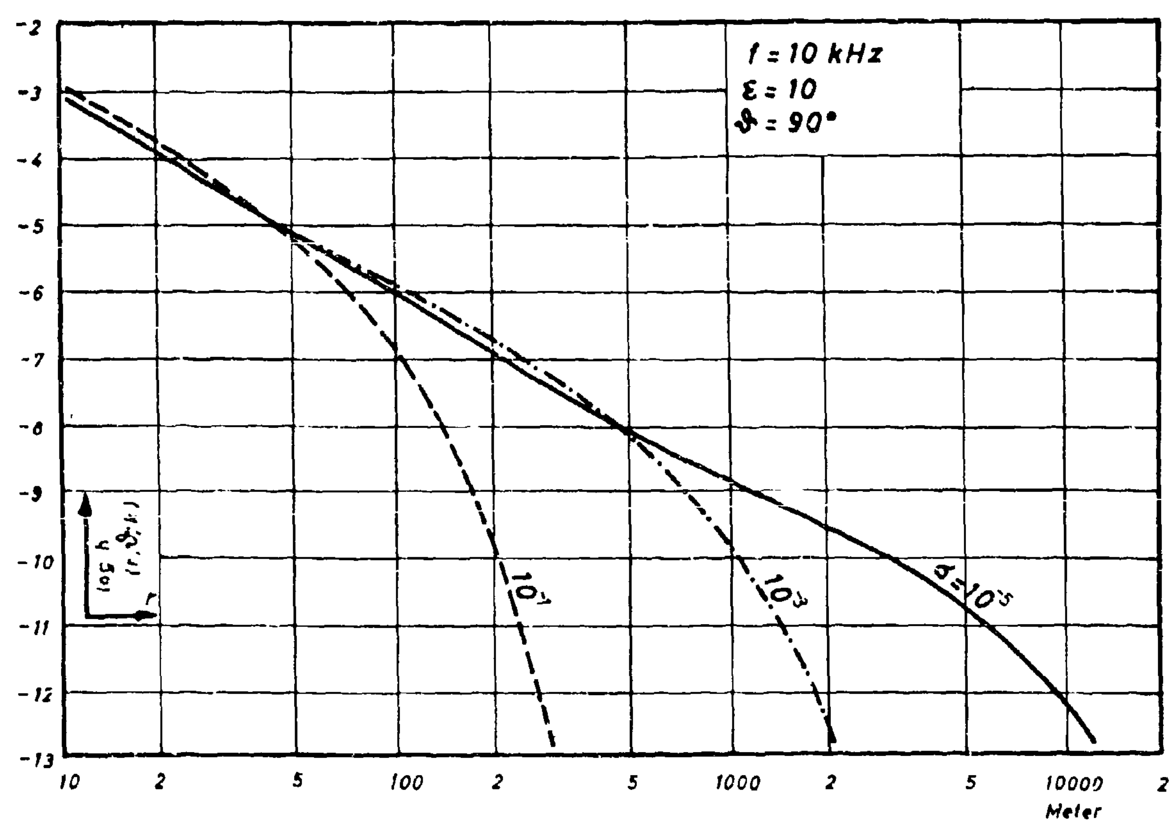
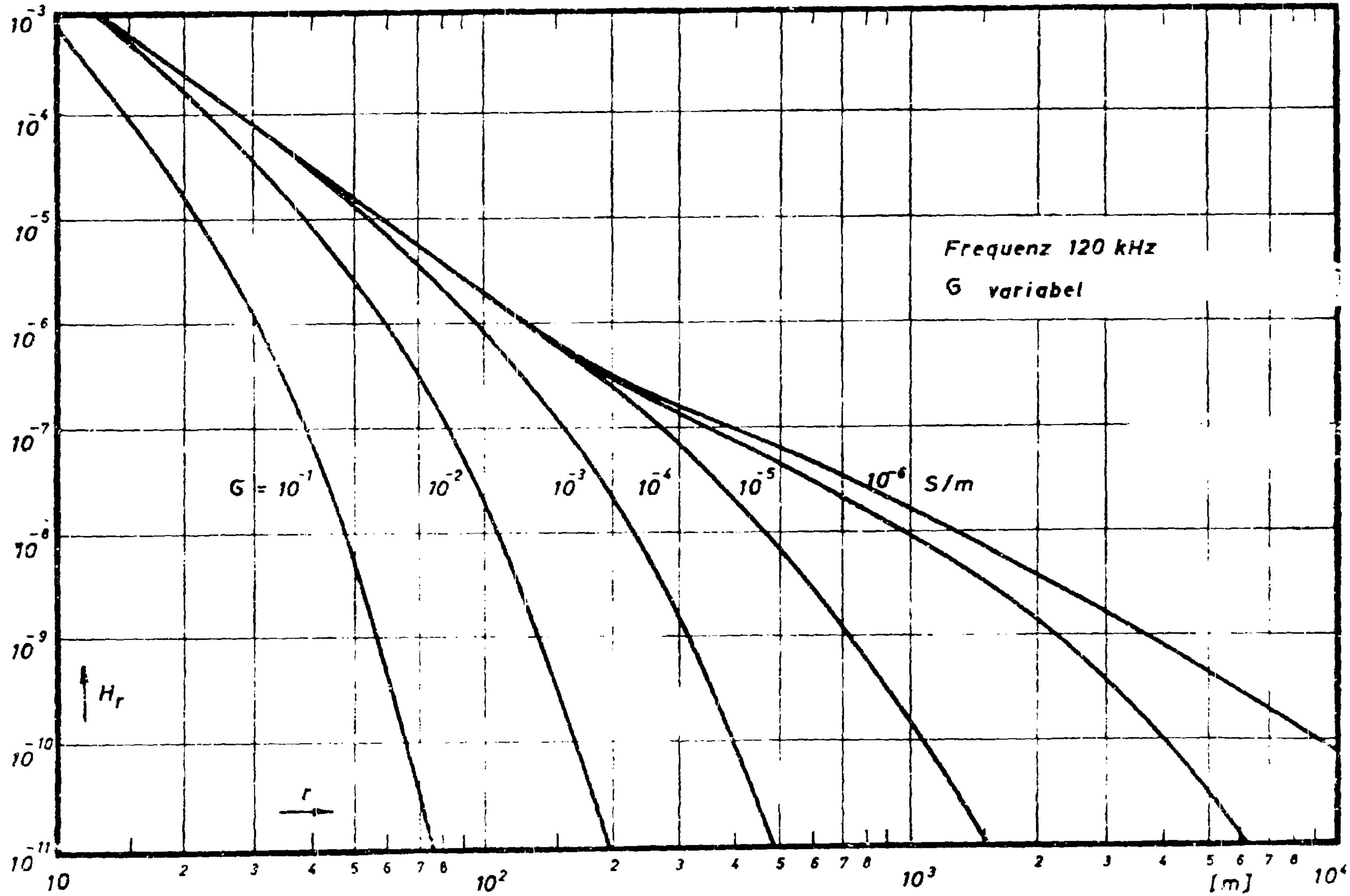
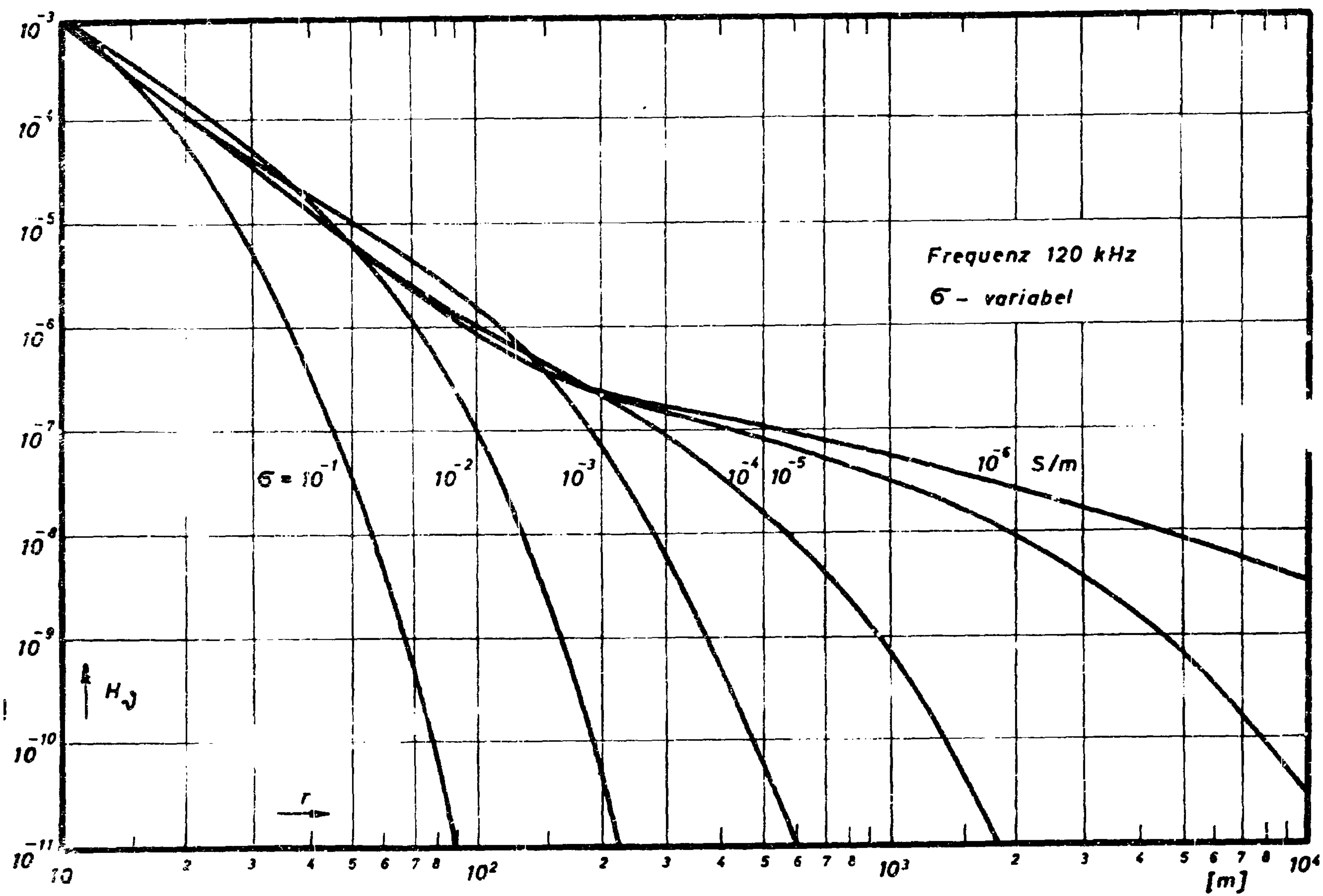

f = 10 kHz
ε = 10
ϑ = 90°
log h (r, ϑ; k)
r
10⁻¹
10⁻³
σ=10⁻⁵
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
10
2
5
100
2
5
1000
2
5
10000
2
Meter

Abb.11



Frequenz 120 kHz
G variabel
G = 10^-1
10^-2
10^-3
10^-4
10^-5
10^-6 S/m
H_r
r
[m]
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10
10^2
10^3
10^4



Frequenz 120 kHz
σ – variabel
σ = 10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶ S/m
H_ϑ
r
[m]

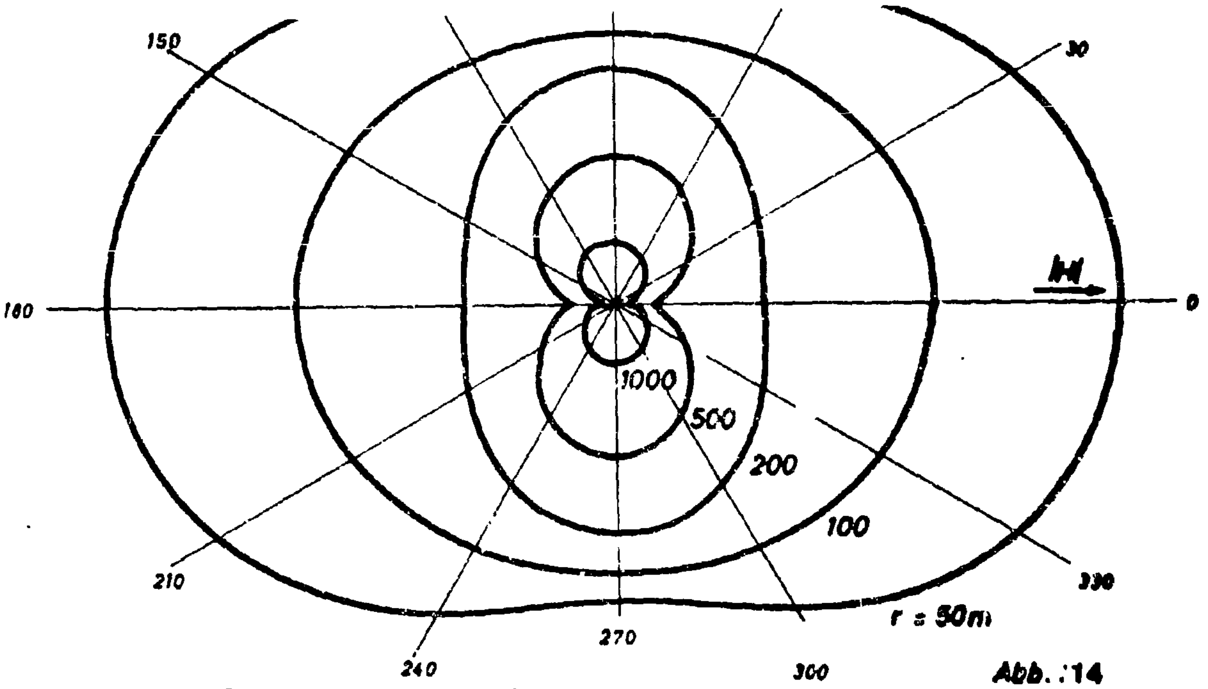
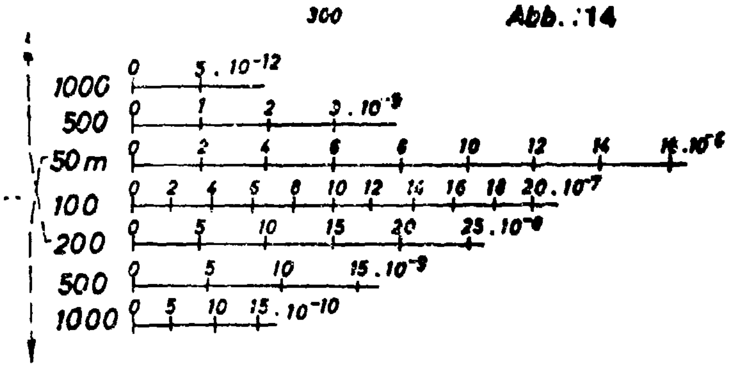


Abb.: 14

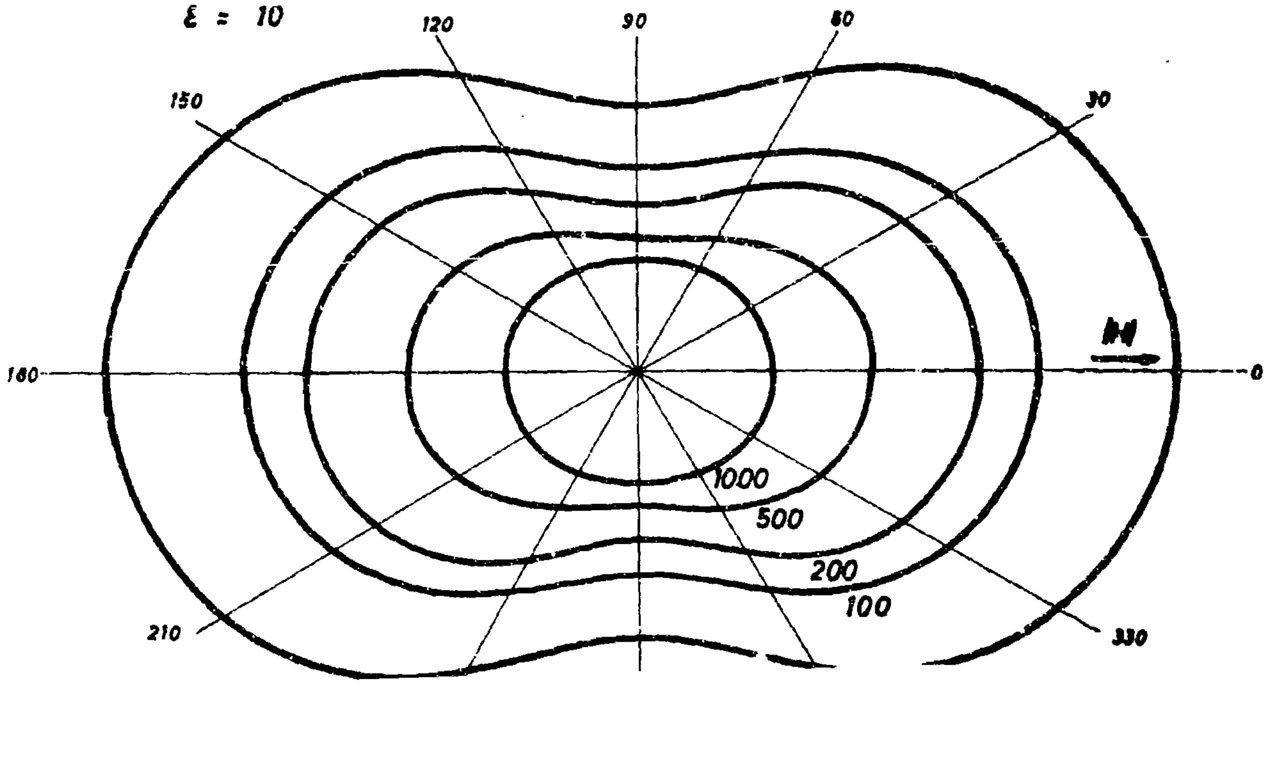
f = 3 kHz
σ = 10^{-2} S/m
ε = 10

Maßstab für ......



f = 3 kHz
σ = 10^{-4} S/m
ε = 10

Abb.: 15



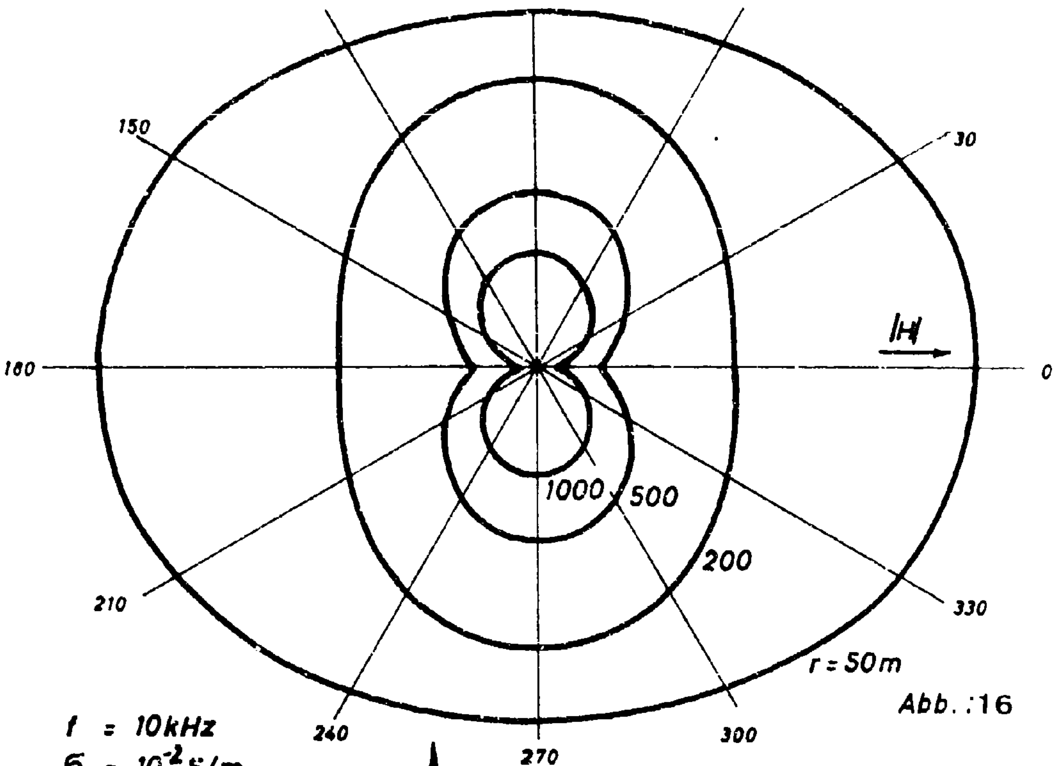
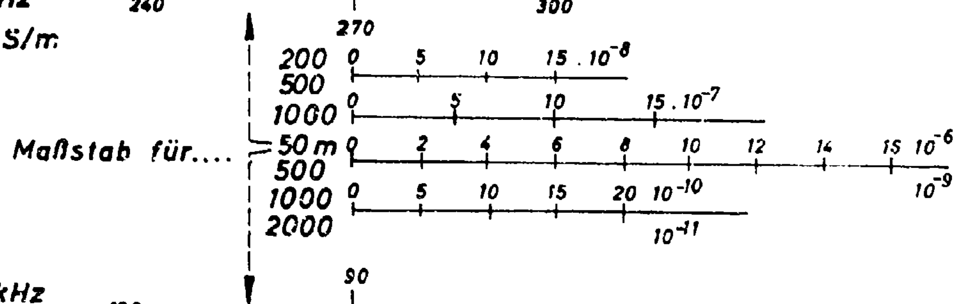


Abb.: 16

$f = 10\,kHz$
$\sigma = 10^{-2}\,S/m$
$\varepsilon = 10$



$f = 10\,kHz$
$\sigma = 10^{-4}\,S/m$
$\varepsilon = 10$

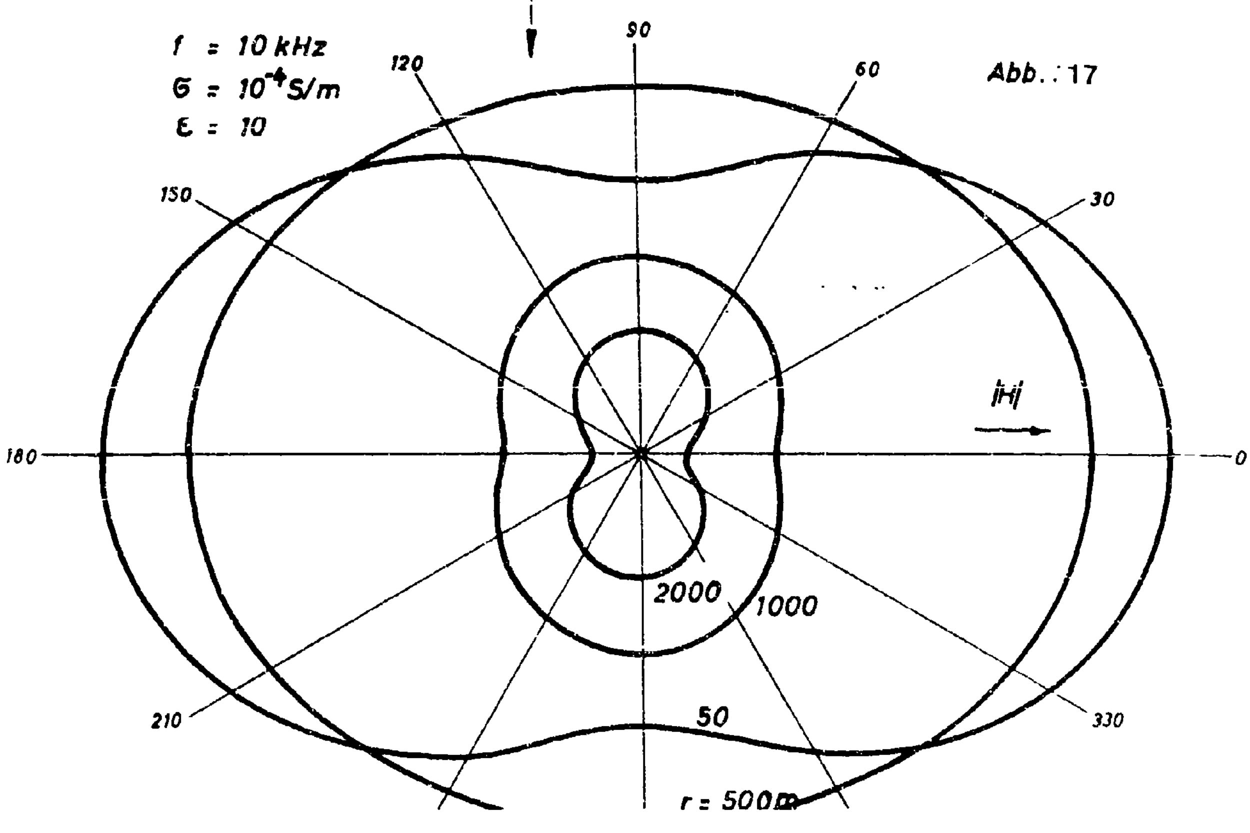


Abb.: 17

Antennendiagramm

$\nu = 120\ kHz \quad \sigma = 10^{-4}\ S/m$

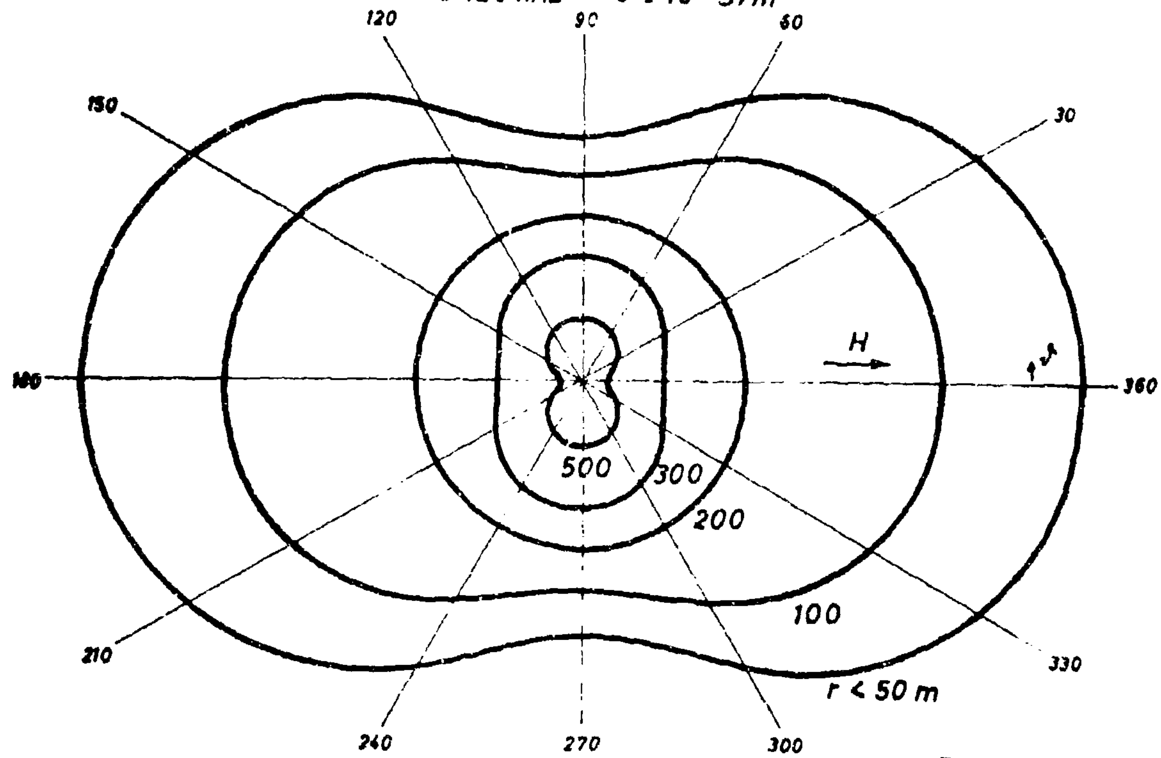


Fig.18

$\nu = 120\ kHz \quad \sigma = 10^{-2}\ S/m$

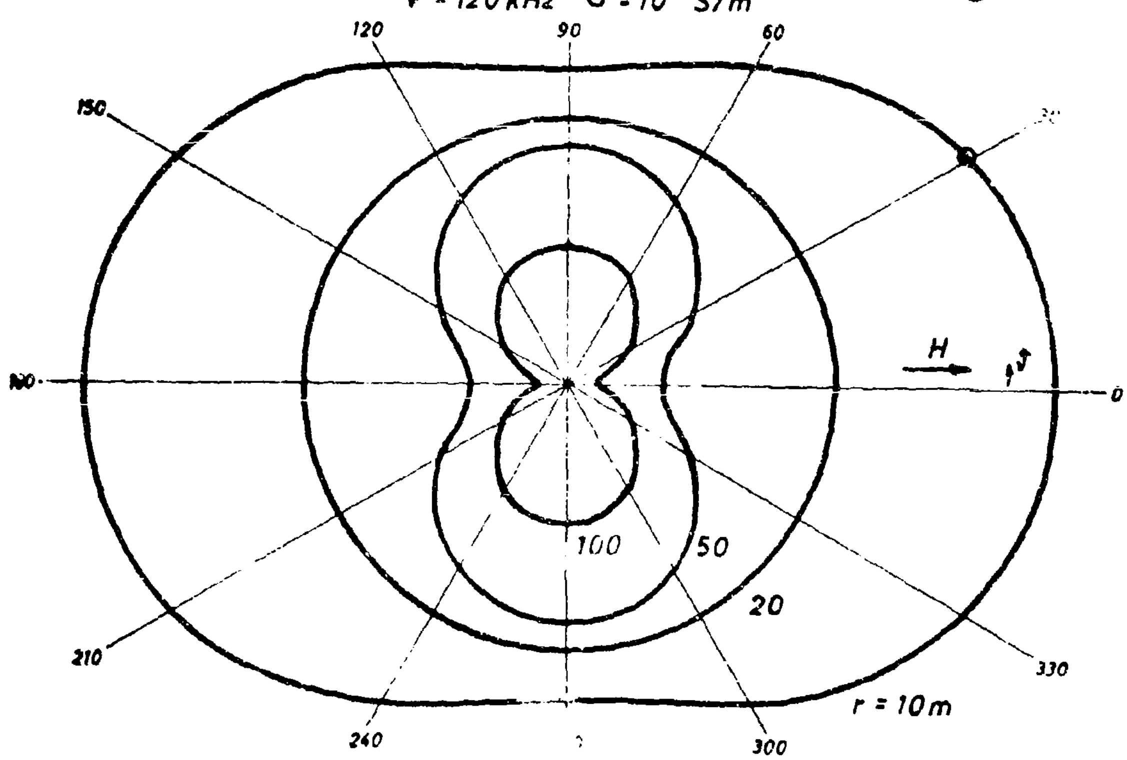


Fig.: 19

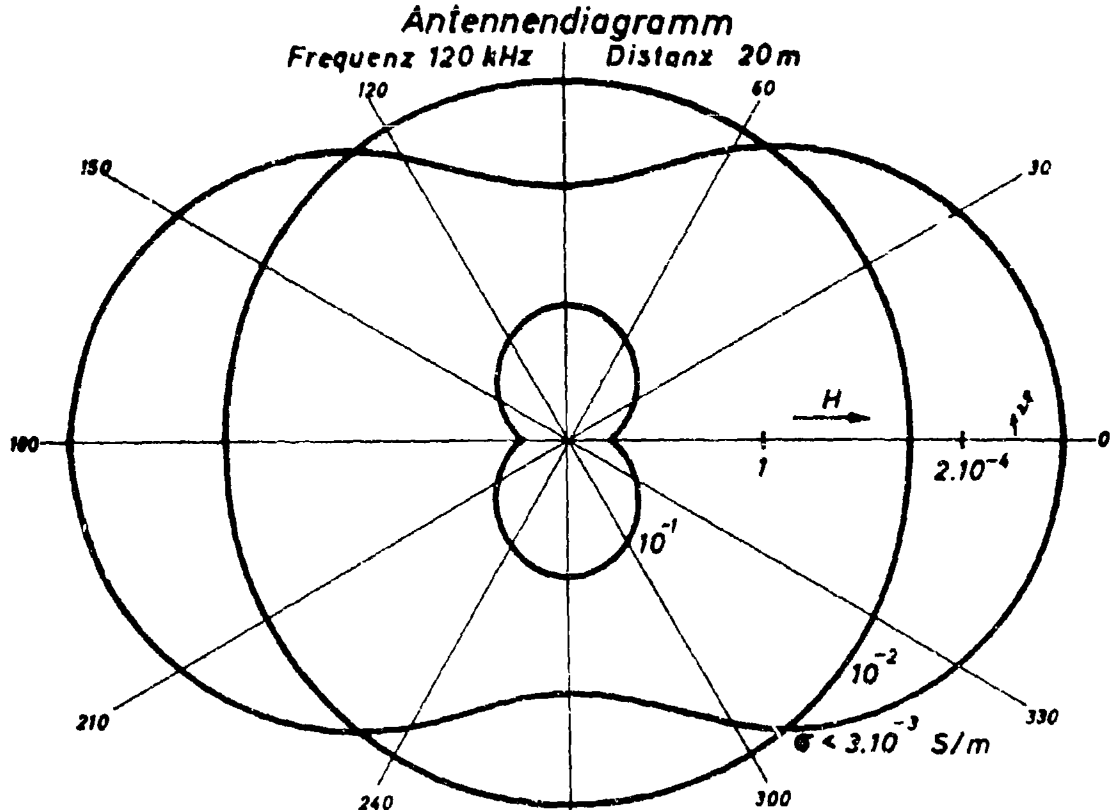

Antennendiagramm
Frequenz 120 kHz
Distanz 20 m
120
60
150
30
180
0
H
1
2.10⁻⁴
10⁻¹
10⁻²
210
330
σ < 3.10⁻³ S/m
240
300

Fig. 20

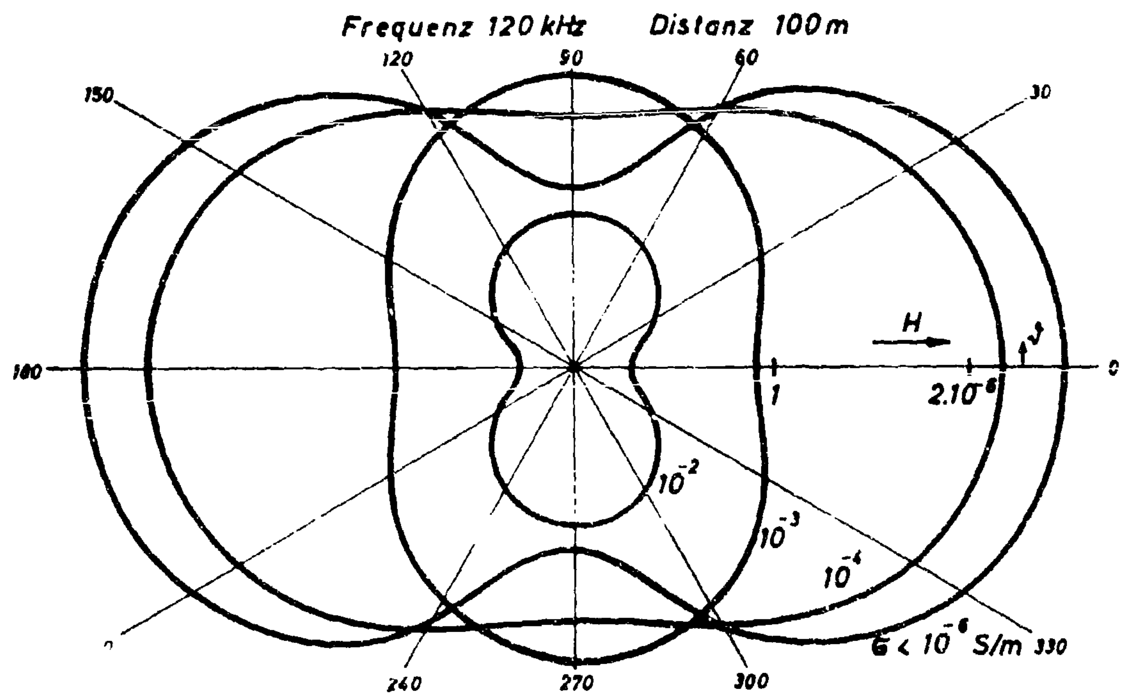

Frequenz 120 kHz
Distanz 100 m
120
90
60
150
30
180
0
H
1
2.10⁻⁶
10⁻²
10⁻³
10⁻⁴
σ < 10⁻⁶ S/m
330
240
270
300

Fig.: 21

1. Transmitting antennas

S.A. I:
type: iron-core coil; iron rod length: 100 cm; sheet material IV; iron cross section: 6 cm^2; turns number: 2 x 96; conductor: copper, 2 mm diam.; inductivity: 3.2 mH; ohmic resistance: 185 mohms; taps at ± 25 turns.

S.A. II:
type: iron-core coil; iron rod length: 100 cm; iron cross section 3.5 cm^2; turns number: 2 x 450; conductor: copper, 0.75 diam.; inductivity: 80 mH; ohmic resistance: 3.1 ohms; taps at ± 25 turns.

These antenna forms did not perform satisfactorily, because the effective surface was too small and the losses in the iron core werde too large.

S.A. III:
type: air-core coil; diameter: 98 cm; winding width: 2 cm; winding height: 1 cm; turns number: 40; conductor: copper, 1.2 diam.; inductivity: 5 mH; ohmic resistance: 1.1 ohms;

S.A. IV:
type: air-core coil; diameter: 1 m; turns number: 100; conductor: copper, 1 mm diam.; inductivity: 23 mH; ohmic resistance: 1 ohm; rigid frame.

S.A. V:
type: air-core coil; diameter: 1 m; turns number: 60; conductor: copper, 1 mm diam.; inductivity: 11 mH; ohmic resistance: 5 ohms; rigid frame.

S.A. VI:
type: square frame; area: 1.4 m^2; turns number: 60; conductor: copper- stranded wire, 2.5 mm^2; inductivity: 15 mH; ohmic resistance: 2.1 ohms;

In this antenna, the copper-stranded wire is welded as a bunch in a flexible plastic hose. Thus, the winding can be removed from the frame and folded up, the frame itself being collapsible. Transportation of the antenna is therefore very easy.

S.A. VII:
type: rectangular frame; area: 17 m^2; turns number: 2 x 15; conductor: copper-stranded wire, 1.5 mm^2; inductivity: 12 mH; ohmic resistance: 13.5 ohms;

This antenna was suspended in the "Bunte Kluft" in St. Gertraudi and could be rotated about its vertical axis.

S.A. VIII:
type: square loop; area : 40 x 40 = 1,600 m^2; turns number: 3; conductor: copper, 2.5 mm^2; inductivity: 20 mH; ohmic resistance: 3 ohms.

In order to attain these dimensions, the antenna had to be firmly established at a suitable site at St. Gertraudi in two shafts and in two connecting galleries.

S.A. IX:
= S.A. VIII with the following modifications: turns number: 10; conductor: aluminium, 135 mm^2.

Thus it was possible to get antenna currents of up to 40 amperes.

S.A. X:
type: rectangular frame; area: 4 x 4 = 16 m^2; turns number: 10; conductor: copper-stranded wire, 4 mm^2, plastic insolated, special insolation with PVC-hose; inductivity: 1.13 mH; ohmic resistance: 0.22 ohms; resonance frequency: 130 kHz; resonance current: 3.4 amperes; resonance voltage: 13,000 v_{pp}; range (through rock): 1,400 m.

The frame is fed from the laboratory to the first turn via Lecher wires, by means of a 1 kW-transmitter.

S.A. XI:
type: pentagonal frame, collapsible; area: 1.5 m^2; turns number: 16; conductor: copper-stranded wire, 1.6 mm^2; inductivity: 780 µH; ohmic resistance: 0.8 ohms; weight: ~ 6 kg; resonance current (antenna fed by means of a portable 5-W-transmitter, described in [12]): 1.4 amperes; resonance voltage: 2,000 v_{pp}; quality: 185.

E.S.P. I:
type: air-core coil; area: 1290 cm^2; turns number: 10 ; conductor: copper, 0.8 diam.; inductivity: 75 µH; ohmic resistance: 0.49 ohms

With this antenna a calibration field was produced with which the field strength meters were calibrated.

Helical antennas

W.A. I:
length: 13.6 m; cross section: rectangular, 1 x 1.8 m; turns number: 161; pitch: ~ 0.9°; studied frequency range: 10 - 600 kHz; lowest resonance frequency: 53 kHz.

W.A. II:
length: 6.8 m; cross section: rectangular, 1 x 1.8 m; turns number: 161; pitch: ~ 0.45°; studied frequency range: 4 - 120 kHz; lowest resonance frequency: 51 kHz.

W.A. III:
length: 13.6 m; cross section: rectangular, 1 x 1.8 m; turns number: 312; pitch: ~ 0.45°; studied frequency range: 400 Hz - 250 kHz; lowest resonance frequency: 24 kHz.

W.A. IV:
length: 1.92 m; cross section: circular, 4 cm diam.; turns number: 1,068; studied frequency range: 4 - 600 kHz;

H I:
length: 1.93 m; diameter: 4 cm; turns number: 848; pitch: ~ 0.9°; wire thickness: 0.8 mm; wire length: 108 m; ground area: 1,250 cm^2; lowest resonance frequency: 1.91 MHz; quality: 350; R_0 = 30 ohms (input impedance $|Z| = R_0\sqrt{2}$)

H II:
length: 2 m; diameter: 1/π m; turns number: 200; pitch: ~ 0.6°; wire thickness: 1,5 mm; wire length: 200 m; ground area: 1,250 cm^2; lowest resonance frequency: 0.756 MHz; quality: 41.3; R_0 = 170 ohms.

H I, submerged in water:
lowest resonance frequency: 50 kHz; quality: 1.4; R_0 = 75 ohms;

H II, submerged in water:
lowest resonance frequency: 25.9 kHz; quality: 2.24; R_0 = 59 ohms.

The following antennas are all fed in the middle, without grounding. The index W means antenna submerged in water.

	H 848 H 848 W	H 200 H 200 W	H 600	H 772 H 772 W	H 1362
length [cm]	192.8	200	200	202	300
diameter [cm]	4	$1/\pi.10^2$	$1/\pi.10^2$	$1/\pi.10^2$	12.72
L_1 [μH/m]	0.351	0.956	8.86	14.2	3.5
L_{1w} [mH/m]	-"-	-"-		-"-	
C_1 [pF/m]	16	45	62	51	26
C_{1w} [pF/m]	$18.8.10^3$	26.10^3		141.10^3	
Z [kohms]	4.69	4.6	11.95	16.7	11.6
Z_w [kohms]	133.10^{-3}	194.10^{-3}		322.10^{-3}	
f_r [kHz]	3,462.7	1,152.3	383.9	294.2	553.29
f_{rw} [kHz]	101	49.0		5.48	
R_0 [ohms]	35.3	68.0	116.0	85	65
R_{0w} [ohms]	91	70.0		122	
Q	208	102	183	318	282
Q_w	2.40	4.4		3.66	
b [kHz]	15.6	11.3	2.08	0.925	1.97
b_w [kHz]	42.0	11.1		1.5	

2. Receiving antennas

E.A. I:
type: ferrite antenna; length of ferrite rod: 47.5 cm; diameter: 1.5 cm; cross section: 1.77 cm^2; turns number: 2 x 500; inductivity: 800 mH; ohmic resistance: 135 ohms; shielded against electric fields by means of aluminium foil.

E.A. II:
type: slender toroidal solenoid
Its electrical performance data were very unfavorable so that it was not used for further measurements.

E.A. III:
type: cylindrical coil without core; diameter: 45 cm; turns number: 1,000.

E.A. IV:
type: ferrite antenna; five ferrite rods arranged along the edges of a prism with a regular pentagon as the base plane. turns number: 5 x 1,600; coil lengths: 15 cm; inductivity: 5 x 1.6 H; ohmic resistance: 5 x 50 ohms; optimum edge length of the pentagon: 15 cm.

E.A. V:
type: ferrite antenna; length: 65 cm; ferrite material: 1100N22 Siemens, Munich; turns number: 3,000; inductivity: 2 H; ohmic resistance: 135 ohms; coil in the middle of the rod.

E.A. VI:
type: laminated iron core coil; length of iron core: 100 cm; iron core made of metal sheet strips, Hyperm 766, Krupp Widia, Essen; cross section: 8 cm^2; turns number: 2 x 1,000; inductivity: 2.2 H; ohmic resistance: 56 ohms; μ_{tor} = 80,000; At the measuring frequencies used so far (3 and 10 kHz) this design is not superior to the types IV and V. At lower frequencies, however, it supposed to be paramount.

At the receiver input E 2 [13] E.A. IV, V, VI yielded a voltage of 1 µv at a field strength of

	f = 3 kHz	f = 10 kHz
E.A. IV	2.32×10^{-12}	0.73×10^{-12} Wb/m^2
E.A. V	6.8×10^{-12}	2.42×10^{-12} Wb/m^2
E.A. VI	3.25×10^{-12}	2.63×10^{-12} Wb/m^2

F.A. V:
type: ferrite antenna; length: 48 cm; diameter: 2 cm; turns number: 1,200; inductivity: 450 mH; material: 1100N22 Siemens,

Munich; coil in the middle of the rod. This antenna was in- ied as a direction finder antenna in Cardanic suspension.

F.A. VI:
type: ferrite antenna; length: 40 cm; diameter: 1.3 cm; turns number: 2 x 50; inductivity: 1.7 mH; material: 550N25 Siemens, Munich, slotted rod.

F.A. VII:
type: ferrite antenna; length: 98 cm; diameter: 2 cm; turns number: 1,200; coil in the middle of the rod; material: 1100N22 Siemens, Munich.

VII. Conclusions

The transmitting and receiving antennas used for VLF project studies have been summarized. Examinations of (V)LF antenna properties shall be continued also in the future. The optimization of helical antennas is going to be studied in a detailed report.

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13. ABSTRACT
This is a description of all the transmitting and receiving antennas that have been used for VLF project studies. The antenna efficiency is discussed and helical transmitting antennas are described in a special chapter. Various diagrams plotted in accordance with the described antenna measurements are given.

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List of antennas used so far						

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